RESPONSE OF THE PLANARIAN, DUGESIA, TO VERY WEAK HORIZONTAL ELECTROSTATIC FIELDS [1]

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A deep-seated, persistent, rhythmic nature, with periods identical with or close to the major natural geophysical ones, appears increasingly to be a universal biological property. Striking published correlations of activity of hermetically sealed organisms with unpredictable weather-associated atmospheric temperature and pressure changes, and with day to day irregularities in the variations in primary cosmic and general background radiations, compel the conclusion that some, normally uncontrolled, subtle pervasive forces must be effective for living systems. The earth's natural electrostatic field may be one contributing factor.

A number of reports have been published over the years advancing evidence that organisms are sensitive to electrostatic fields and their fluctuations. More recently Edwards (1960) has found that activity of flies was reduced by sudden exposures to experimental atmospheric gradients of 10 to 62 volts/cm., and that prolonged activity reduction resulted from gradient alternation with a five-minute period. In 1961, Edwards reported a small delay in moth development in a constant vertical field of 180 volts/cm., but less delay when the field was alternated. The moths tended to deposit eggs outside the experimental field, whether constant or alternating, in contrast to egg distribution of controls. Maw (1961), studying rate of oviposition in hymenopterans, found significantly higher rates in the insects shielded from the natural field fluctuations, whether or not provided instead with a constant 1.2 volts/cm. gradient, than were found in either the natural fluctuating field, or in a field shielded from the natural one and subjected to simulated weather-system passages in the form of a fluctuating field of 0.8 volts/cm.

A study in our laboratory early in 1959 (unpublished) by the late Kenneth R. Penhale on the rate of locomotion in *Dugesia* suggested strongly that the rate was influenced by the difference in charge of expansive copper plates placed horizontally in the air about six inches above and closely below a long horizontal glass tube of water containing the worms. Locomotory rates in fields of 15 volts/cm. (+ beneath the worms) were compared with those in fields between equipotential plates. The fields were obtained with a Kepco Laboratories, voltage-regulated power supply. A comparable study with the marine snail, *Nassarius,* by Webb, Brown and Brett (1959), employing a Packard Instrument Co., high-voltage power supply, confirmed the occurrence of such responsiveness to vertical fields of 15 to 45 volts/cm., and advanced evidence that the response of the snails displayed a daily rhythm.

More recently, it was demonstrated that mud-snails, even while submerged in sea water, were able to resolve a horizontal field difference of 2 volts/cm. in the

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air at right angles to their bodies, and to exhibit a characteristic orientational response (Webb, Brown and Schroeder, 1961). The fields were obtained with B batteries. The snails appeared able also to distinguish the direction of the very weak gradient across their bodies. The character of the electrostatic response was altered simply by changing from South to East the compass direction in the earth's field in which the response was assayed. There seemed to be an influence upon the electrostatic response, by some natural force the effectiveness of which altered with geographical orientation of the organisms.

The following study was made in order to determine whether a comparable sensitivity to very weak electrostatic fields obtains for a common fresh-water planarian, and if so, to learn more concerning its properties.

Methods and Materials

The turning of planarian worms, *Dugesia dorotocephala,* was assayed as they moved forward from an initially enforced orientation in a weak three-light field (Brown, 1962). The three light sources were (1) directly vertical to the initial point in the path, (2) in the horizontal plane directly behind the initially oriented worm, and (3) horizontally 90° to the right of the starting point. In response to this configuration of illumination, the mean path of samples of the worm population, photonegative, always included turning of the worms to the left. The strength of left-turning response was rendered quantitative by recording, to the nearest 5°, the points at which the worms crossed the arc of a circle of one-inch diameter centered at the starting point of the worm. Clockwise turning of the individuals was recorded in positive degrees of arc and counterclockwise turning by negative degrees of arc (Fig. 1) from a mean path directly forward (0°).

The effects of horizontal electrostatic-field gradients were determined by comparing the mean values for 15-path samples in field gradients modified by rendering two aluminum plates in air (Fig. 1), to right and left, equipotential or with potential difference of 45 volts with + to right or + to left. The effects were studied under experimental conditions in which other variables included: (1) magnetic compass direction of the initial, enforced orientation of the worm, which was modified by rotating the whole apparatus to the desired compass direction; (2) time of day the experiment was conducted; and (3) experimental alteration of the natural magnetic field by a horizontal bar magnet centered an appropriate distance beneath the apparatus.

In practice, the worms were placed in a $3\frac{3}{4}$-inch glass Petri dish in 0.5 cm. of water and the dish centered on polar-coordinate paper. This was set upon the floor of a blackened wooden box. The upper portion of one side of the box was open to the observer. In the roof of the box, 16 inches high, was a small light source. The horizontal light sources were onion-skin-covered ends of 10 mm. solid glass tubing, enclosed in black shielding. Through these light was transmitted into the box from a $7\frac{1}{2}$-watt incandescent lamp firmly attached to the outside of the box. Symmetrically to right and left of the Petri dish were large 7×9 inch aluminum plates, sandwiched between glass plates darkened with flat black paint. The level of the worm starting-point was close to an axis between the centers (horizontal and vertical) of the two plates. The aluminum plates were about 8 inches apart, thus giving about a 2-inch air space between each plate and the

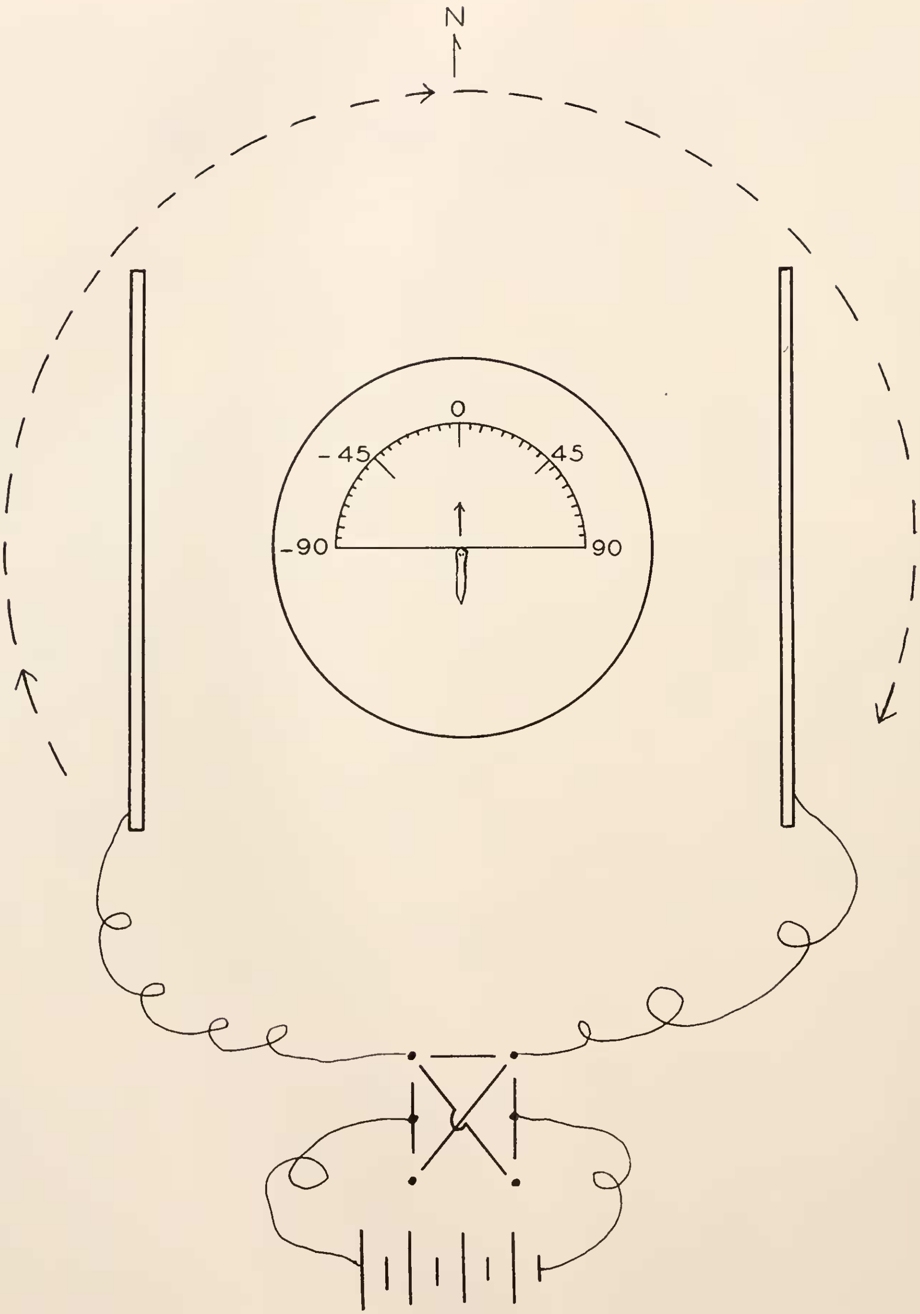

FIGURE 1. The apparatus organization employed in this study, including Petri dish, polar coordinate grid, and aluminum plates. Three-light arrangement is not illustrated. Broken circular line indicates apparatus rotatable relative to earth's geographic field.

Petri dish. The whole visual environment of the orienting worms comprised a rigid system which was constant as the apparatus was rotated in the earth's field. This apparatus was always used in a darkened cubicle to minimize extraneous illumination. As many as four identically constructed pieces of equipment were in operation concurrently, and sequentially, during the course of the study.

The overall average field gradient contributed by the plates was about 2 volts per cm. when these were connected with a 45-volt B battery, with the polarity alterable by a pole-reversing switch. When the battery was disconnected by a toggle switch (SPDT) the plates were simultaneously directly interconnected to assure their equipotential state.

The experiments in any given series were conducted at the same time each day to avoid any complicating factor introduced by a daily rhythm. In addition, each experiment extended over two or more months to randomize any lunar daily influence which might obtain comparable to those well-established to occur for response to very weak magnetic fields.[2]

Results

Response of South-directed worms in the morning: The first series of experiments involved the responses of worms initially always directed magnetic South in the earth's field.The observations were made sometime between 8:30 and 11 A.M. and consisted of two groups of four assays each. Each of the two groups included the determination of the mean paths of 15-worm samples under each of four conditions, two controls (equipotential plates) and two experimentals, + to left (+L) and + to right (+R). The order of the four was selected arbitrarily and differed steadily from one group to the next throughout the two-month experimental period, September 20 through November 17, 1961. The charge across the plates was altered by a person other than the observer. The observer was never informed as to conditions in effect until each day's double series was completed.

The results of this experiment, in which the difference between each, +R and +L, from the mean of the two controls in the group was computed, are plotted in Figure 2. Were the worms incapable of differentiating between the equipotential plates and those possessing a potential difference, the average difference between these would be zero, and the points would be expected to vary randomly about zero. As is evident from inspection of Figure 2, the mean was highly significantly to the right of zero. The mean was $+2.342 \pm 0.342°$ ($t = 6.87$, $N = 152$, $P < 10^{-10}$). These results leave no reasonable doubt that the change from equipotential plates to the 45-volt difference was effecting a mean clockwise turning of *Dugesia*.

The relation of response to compass direction: The foregoing experiment was repeated during the period October 24, 1961, through February 27, 1962, initially by observers different from the one concerned in the first experiment. Five different observers, employing four sets of equipment, eventually contributed to the data. Again, the observations were always made between 8:30 and 11 A.M. But now the effects of the 45-volt difference between the plates, expressed as difference from the equipotential plates, were determined not simply with South-directed apparatus,

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but with apparatus directed in each of eight compass directions. A single observer on any given day would arbitrarily select one of the compass directions. Otherwise the observations were made just as in the first experimental series. All observers contributed to data from each compass direction. The observers were now informed, however, as to the experimental conditions obtaining, but four of the five observers were uninformed of previous work, or even of the nature of the problem. The results of the four-month study are summarized in Table I, and the frequency distribution for each compass direction illustrated in Figure 3.

There was reasonably good confirmation of the earlier South-directed "uninformed" experimental series. However, a clear compass-direction effect was now evident. When the apparatus was southerly directed, the increase in potential gradient turned the worms clockwise, when northerly directed, counterclockwise, with graded differences between these directions. More particularly (see Figure 4), the results suggested that the axis of the compass-direction effect was a S-SE to N-NW one instead of a magnetic N-S one.

Relationship of response to time of day: While this last experimental study was under way data were being gathered from occasional comparable series run between 2 and 6 P.M., commencing on September 15, 1961. These provided a strong

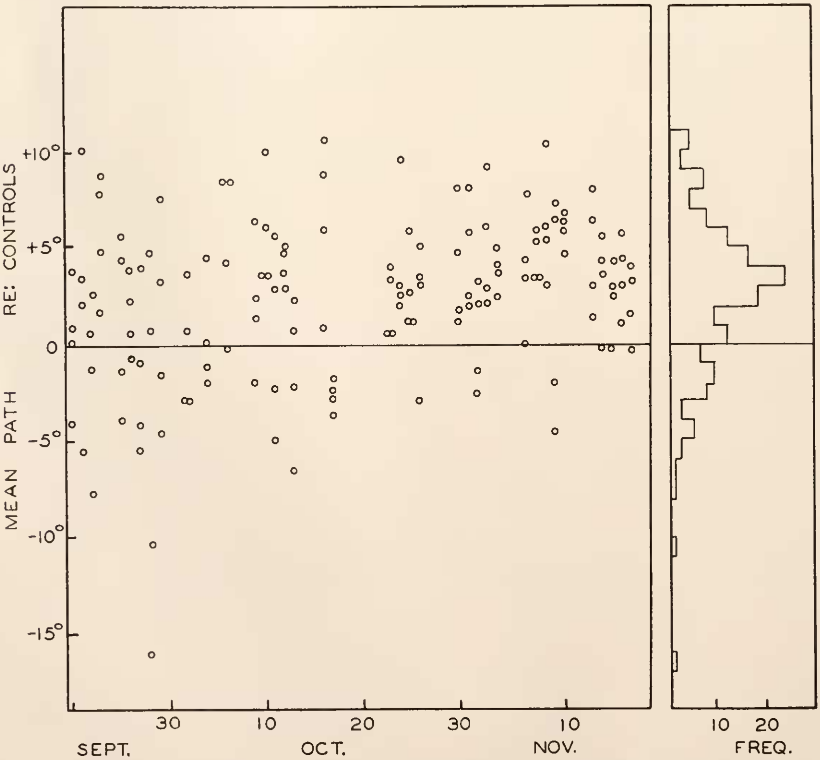

FIGURE 2. The differences between path of worm samples (15 paths) in a 2-volt/cm. right-angle gradient and path in the same experimental series in an equipotential field.

TABLE I

Morning paths

Direction	Mean	S.E.	t	N	Probability
N	−1.325	±0.605	2.13	64	<.05
NE	−1.125	±0.354	3.09	76	<.005
E	+1.330	±0.433	2.92	56	<.005
SE	+1.950	±0.498	3.92	84	<.001
S	+1.805	±0.549	3.29	86	<.005
SW	+2.275	±0.476	4.74	80	<.001
W	−0.920	±0.502	1.41	78	<.20
NW	−1.350	±0.424	3.18	80	<.005

suggestion that afternoon values were not showing the same form of compass-direction relationship as the morning ones. Instead, the results suggested that there was an inversion of the compass-direction effect. This question was eventually pursued more systematically and studied until May 1, 1962. It is evident from Table II and Figure 4 that for two directions for which moderately extensive data were obtained, NW and S, the electrostatic field effect shows a clear inversion of the afternoon values relative to the morning ones. That the afternoon responses for each direction were different from the morning ones was far more clearly apparent

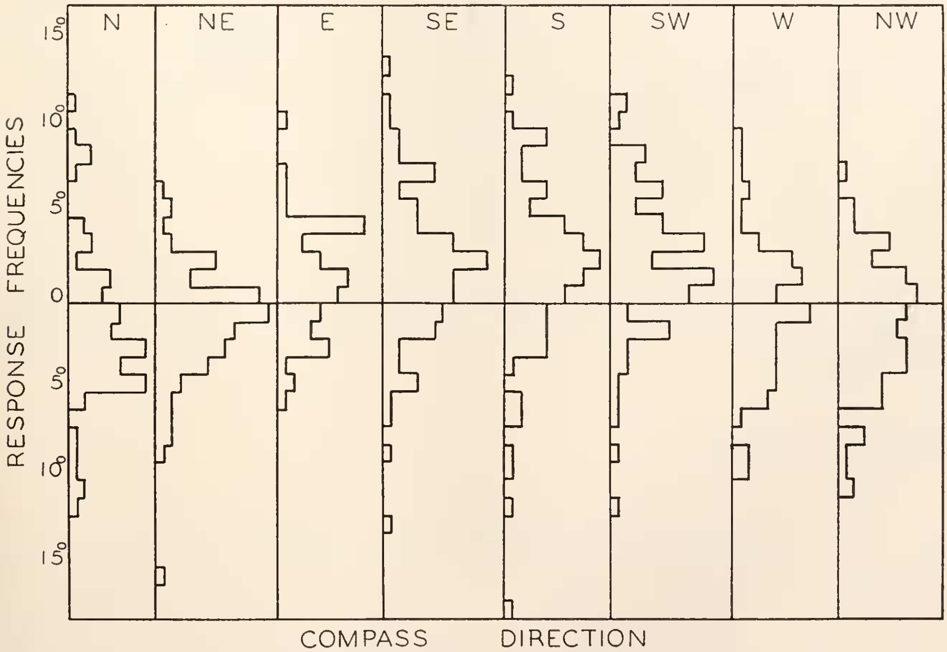

FIGURE 3. Frequency distributions of the differences between paths of worm samples in a 2-volt/cm. right-angle gradient and path in the same experimental series in an equipotential field for each of eight compass-directional orientations.

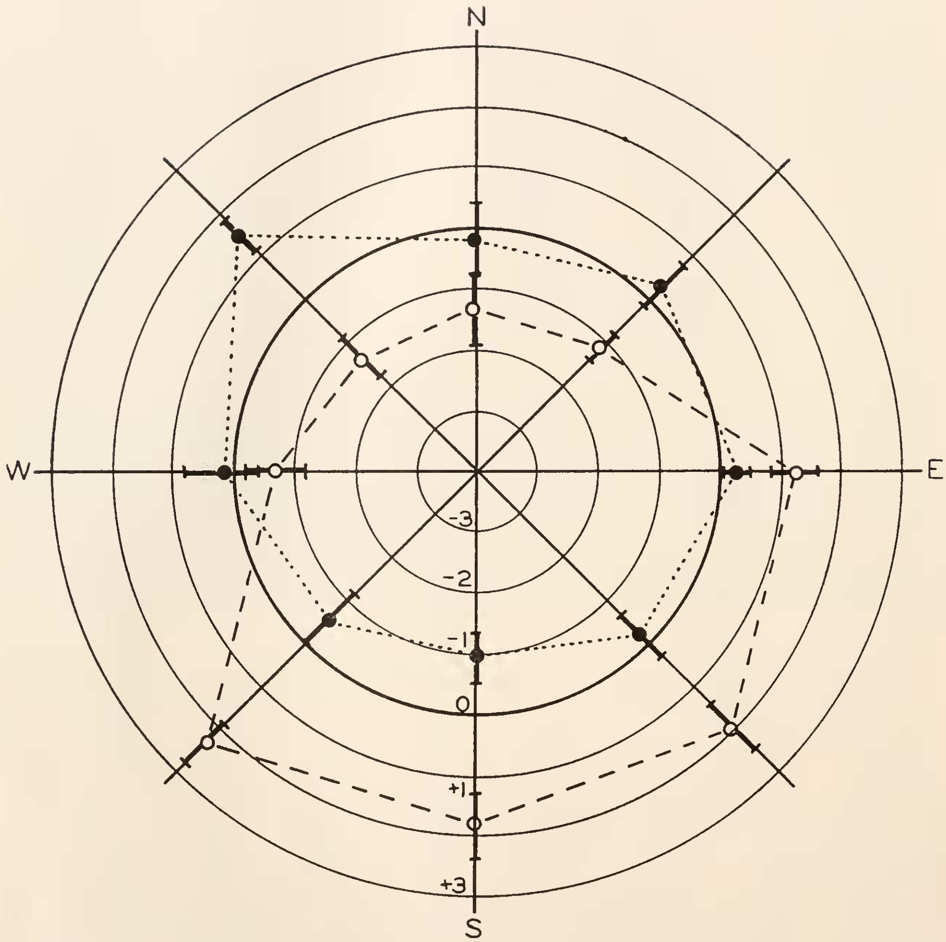

FIGURE 4. Comparison of the compass-direction effect upon response to electrostatic gradient for morning (dashed line) and afternoon (dotted line) hours. Degree of left turning is indicated by concentric circles inside heavily inked one, and right turning by concentric circles outside of it.

upon finding 6 of the 8 directional differences (NE, E, SE, S, SW, and NW) statistically significant.

Influence of experimental magnetic-field changes on response: Since there was conspicuously a compass-directional relationship of the character of the response to the 2 volt/cm. change in electrostatic field it became of interest to learn whether this was directly dependent upon responsiveness of the worms to the magnetic field. Consequently, an additional experiment was conducted between February 17 and April 11, 1962. This comprised, until March 13, observing in the morning the effects upon mean paths of the electrostatic-field difference for North- and South-directed planarians and for North-directed ones under experimental conditions of an artificial magnetic field differing from the earth's only in that the natural 0.17-

TABLE II

Afternoon responses

Direction	Mean	S.E.	t	N	Prob.	Difference from A.M.	S.E. diff.	t	N	Prob.
N	− .12	±0.48	0.25	42	<.9	+1.20	±0.772	1.55	106	<.20
NE	+ .37	±0.53	0.70	51	<.5	+1.52	±0.634	2.40	127	<.02
E	+ .33	±0.25	1.32	178	<.2	−1.00	±0.499	2.00	234	<.05
SE	− .20	±0.46	0.17	42	<.9	−2.15	±0.678	3.17	126	<.005
S	− .92	±0.46	2.00	62	=.01	−2.73	±0.716	3.81	148	<.001
SW	− .57	±0.54	1.05	40	=.3	−2.85	±0.720	3.96	120	<.001
W	+ .12	±0.56	0.21	41	<.30	+1.04	±0.752	1.38	108	<.20
NW	+1.44	±0.38	3.79	60	<.001	+2.79	±0.569	4.90	140	<.001

gauss North-directed horizontal component of the field was experimentally reversed to become a 0.2-gauss, South-directed one. Upon the basis of response to magnetism, the worms should now receive stimulation closely similar to that normally experienced by South-directed worms. On March 13, one additional condition was added to the series, namely South-directed worms in the earth's field were given experimentally (as a 0.2-gauss field) essentially the magnetic equivalent of a North-directed route.

In practice, each series comprised, in random order, pairs of observations under each of the three or four conditions, with the order, equipotential to non-equipotential plates, in each pair determined by the flip of a coin. The three observers of the worms were uninformed of the order for each pair.

The results of this experiment are shown in Table III. The experiments showed the same qualitative difference between North and South in the earth's field that had been observed in the earlier series similarly conducted in the morning. Evident from the table is the fact that compass-North-directed worms given a South-directed experimental magnetic field, $N_{(S)}$, did not come to behave like South-directed ones, S. Indeed, the experimental reversal of the magnetic field even augmented the characteristic counterclockwise, North-directed response, N. The difference between N and S responses was $1.496 \pm 0.546°$ ($t = 2.74$). The difference between $N_{(S)}$ and S responses was $2.68 \pm 0.522°$ ($t = 5.13$). In fact, the difference between N and $N_{(S)}$, $1.16 \pm 0.501°$, was itself statistically significant ($t = 2.31$).

The difference between S and $S_{(N)}$ is, unlike the difference between N and $N_{(S)}$, in the direction to be expected were the compass-direction effect to result

TABLE III

Influence of experimental magnetic-field reversal

Direction	Mean	Standard error	t	N	Probability
N	−0.493	±0.372	1.325	93	<.2
$N_{(S)}$	−1.65	±0.336	4.91	93	<.001
S	+1.03	±0.400	2.57	93	<.02
$S_{(N)}$	−0.22	±0.524	0.42	50	<.7

from an influence of magnetism. Although the sample of $S_{(N)}$ is only about half the size of the other three experimental conditions, due to the late addition to the series, the difference of $1.25 \pm 0.658°$ suggests that a comparable statistically significant difference would have been demonstrated had the sample been larger.

It is clear that experimental reversal of the magnetic field did not reverse the relative differences in path as did a change in compass direction. The introduction of the weak magnetic fields for each of the two directions simply displaced the response to the weak electrostatic field, either to a less positive orientational one (S) or a more negative one (N). In other words, the effect of the reversed

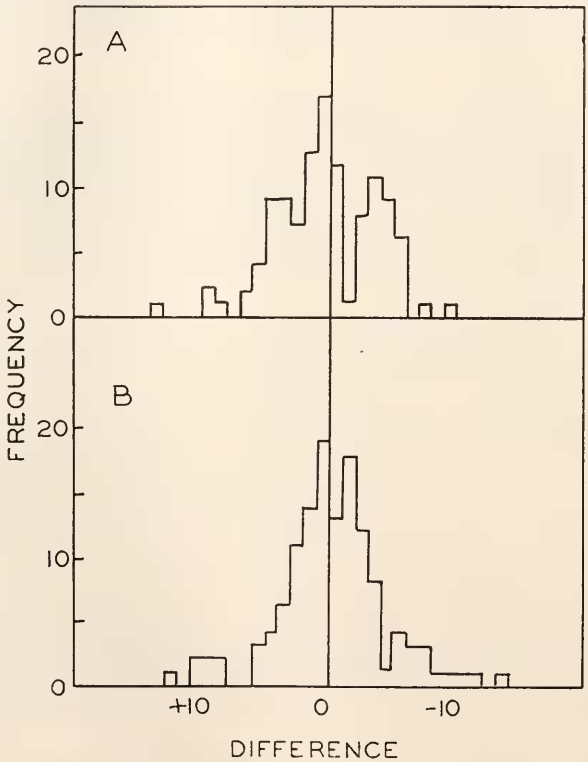

FIGURE 5. Comparison of the frequency distributions of the +R effect minus +L effect for (A) the period November 20, 1961 through March 31, 1962, and (B) the periods September 15 through November 17, 1961 and April 1 through May 1, 1962.

magnetic fields appeared to be simply to displace about 1° to the left the electrostatic response-pattern related to compass directed without altering its form. Therefore, this particular compass-direction effect of electrostatic response is in large measure independent of the previously described geomagnetic compass-response of snails and planarians (Brown, Bennett, and Webb, 1960; Brown, 1962).

Resolution of field direction across body: The data were searched for evidence concerning whether or not *Dugesia* was able to distinguish between a potential difference with positive charge to right and one with positive charge to left. Assuming no capacity of the worms to distinguish between these two conditions, the difference between the two should average zero, and there should be a random distribution of values about zero.

When, however, the morning differences between the effects of the two field orientations, +R minus +L, were examined for all eight compass directions for the whole period of study, October 24 through February 27, a difference of $+0.821 \pm 0.277°$ was obtained ($t = 2.96$; $N = 297$; $P < .005$). Furthermore, within this four-month period the data departed significantly in both directions from a random distribution in time. For example, from December 4 to 23, inclusive, the mean was $-1.31 \pm 0.51°$; $N = 44$, $P < .02$; whereas from December 26 through February 10, it was much more strongly significant and positive $+1.535 \pm 0.408°$; $N = 170$, $P < .001$. The data suggested that for the former period the worms were distinguishing between the two directions of the field and turning away from +R, and during the latter, were distinguishing and turning toward the +R.

A second kind of suggestion that the worms were able to distinguish the two field-directions came from a comparison of the values of the differences between effects of the two fields, +R minus +L, for the morning and afternoon experimental series. The mean difference computed from all data for the afternoon indicated they were turning away from +R, though not statistically significantly so. When the frequency distributions of all the afternoon values for the colder months (November 17 through March 31) were plotted, a bimodality was suggested (Fig. 5A). It thus appeared again that two kinds of response were evident to +R. There was either (1) a tendency to turn weakly toward it, or (2) a tendency to turn more strongly away from it.

This bimodality was significantly less apparent for all the afternoon values obtained for warmer months (September 15 through November 15, 1961; April 1 through May 1, 1962); the frequency distribution for these two periods is shown in Figure 5B. A Chi-square test for significance of a difference between the two populations of values depicted in Figure 5 gave $\chi^2 = 32.05$, when scattered peripheral values were combined to render $N = 12$, or $P < .003$. Such a difference would not be expected unless +R and +L could elicit different responses by the worms. A suggestion of the occurrence of two signs of responses was present also in the frequency distribution of the morning data.

A third kind of evidence pointing to ability of the worms to distinguish between the two field orientations came from a study of differences in variances of the values

TABLE IV

Variances of +R effect minus +L effect

Direction	Var. through May 1	N through May 1
N	21.85	49
NE	23.20	59
E	13.54	111
SE	17.71	63
S	22.86	150
SW	27.20	58
W	21.45	52
NW	12.95	72

of +R effect minus +L effect, with compass direction for all data. These are presented in Table IV. Variance differs in a statistically significant manner with compass direction. It reaches its highest values in the SW- and NE-directed series with minima for E and NW ones. Significance is readily demonstrable by the F test for differences between variances, between minima and maxima in this compass-direction effect (*e.g.*, E to NE, $P < 0.05$; E to SW, $P < .01$; NW to SW, $P < .01$; NW to NE, $P < .05$). It is self-evident that such differences with compass direction could not be expected were +R to be physiologically indistinguishable from +L.

The evidence, taken as a whole, suggests therefore that the relative responses of the worms to +R and +L vary with time, with geographic orientation of the worms, and with hour of the day.

Discussion

In the study which is reported here, the exact values of the fields to which the animals were subjected were never known. The natural field was unquestionably reduced substantially and maximally in the horizontal axis connecting the two equipotential plates, and minimally in all axes at right angles to this, including both horizontal and vertical ones. The important thing for this study was that whatever horizontal potential gradient remained at right angles to the initial path of the worms, the experimental gradient in one direction added 2 volts per cm. to that field, and in the other direction subtracted this amount. By such means it was possible, therefore, to determine whether the animal could resolve such small changes.

The orientation of the worms in the experiment was observed while they were submerged in tap-water whose source was Lake Michigan. Such water is, relative to the surrounding air, a good conductor. Therefore, the overall electrostatic gradient to which the worms were directly subjected was far smaller than the 2 volts/cm. gradient in the air. The value can be estimated to be 6 to 8 orders of magnitude below that in the air as a consequence of the "Faraday-cage effect" of the worm's ambient aqueous medium. To exhibit such responses as the worms did in these experiments would require a sensitivity to essentially static electric gradients of the order of fractions of a microvolt per centimeter.

The significance of this demonstrated sensitivity for animals is apparent. In speculations on the mechanism involved in the reported responses of insects to atmospheric gradients, surface charge has been importantly considered (Edwards, 1960). In the light of the "Faraday-cage action" of every organism's body as it behaves as a volume conductor, it has been difficult to believe that the minute residual gradients within the organism, correlated with the larger atmospheric gradients, could result in any response of individual cells or organs located protectively inside the external boundaries of the organism. The studies with the worms, and earlier studies with the marine snails submerged in sea water (even a slightly better conductor), have proven there exists cellular sensitivity adequate to require a reconsideration of the mechanism of response in such terrestrial organisms as the insects, hamsters (Schua, 1954) and even man (Frey, 1952).

Sensitivities of the order of those established by this study provide one means for an influence of weather-system changes on organisms. Such meteorological changes are not uncommonly accompanied by electrostatic fluctuations more than one hundred times as great as the experimental ones employed in this study. An innate ability of living things to interpret specific parameters of electrical change in their environment may prove to be a partial explanation of apparent forewarnings some organisms have appeared to receive relative to meteorological disturbances.

Ability to resolve small differences in strength of horizontal vectors of atmospheric electrostatics, and their direction as well, can contribute as a navigational aid. This would comprise an electrostatic "compass." Such a compass may be used along with other aids, such as response to magnetic field and visual responses, including use of celestial references.

The earth's atmosphere displays periodic variations in diverse electrical parameters. These relate importantly to movements to the earth with respect to sun and moon. Ability to resolve strength, direction, and frequency and amplitude of oscillations in electrostatic field, can theoretically provide an organism with a means of deriving valuable information as to the period lengths of the natural geophysical rhythms. Both local-time and universal-time components are present in these fluctuations. Responsiveness to electrostatic fields may possibly be one of the normally contributing factors to the timing system of the extraordinary clocks of animals and plants.

Such sensitivity of a protoplasmic system to an electric field as appears to be present renders it probable that protoplasm is far more sensitive to electromagnetic fields of radio-frequency than has generally been conceded, or even reported, up to the present. This possibility is further supported by the correspondingly great sensitivity to extremely weak magnetostatic fields reported elsewhere. It is conceivable that failure to disclose such perceptivity may commonly be a consequence of an inability, to date, to discover an invariable kind of response by the organism to such a stimulus.

The complexity of the response mechanism of the planarians to electrostatic fields as revealed by these studies, and the relationships of the response to both temporal and spatial orientation, certainly suggest the hypothesis that responsiveness to this factor plays still undisclosed and important roles in the lives of terrestrial creatures.

Summary

1. The planarian *Dugesia* is able, even while in water, to perceive a change of 2 volts/cm. in electrostatic gradient in the surrounding air.

2. There is reason to presume that in order to show this response the organism is responding to differences in ambient static gradient of the order of fractions of a microvolt per cm.

3. The strength and character of worm response to a right-angle potential change are related to the direction the worm is oriented in the earth's geographic field, and to time of day.

4. A field-change in South-bound worms in the morning effects clockwise turning. A similar field-change for North-bound worms effects counterclockwise turning. In the afternoon the relationship of electrostatic response to geographic direction is essentially the mirror-image of that of the morning.

5. *Dugesia* is able to distinguish the direction of a gradient across its body.

6. A few of the possible significances of these findings are discussed briefly.

LITERATURE CITED

Brown, F. A., Jr., 1962. Responses of the planarian, *Dugesia*, and the protozoan, *Paramecium*, to very weak horizontal magnetic fields. *Biol. Bull.*, **123**: 264–281.

Brown, F. A., Jr., M. F. Bennett and H. M. Webb, 1960. A magnetic compass response of an organism. *Biol. Bull.*, **119**: 65–74.

Edwards, D. K., 1960. Effects of artificially produced atmospheric electrical fields upon the activity of some adult Diptera. *Canad. J. Zool.*, **38**: 899–912.

Edwards, D. K., 1961. Influence of electrical field on pupation and oviposition in *Nepytia Phantasmaria* Stkr. (Lepidoptera: Geometridae). *Nature*, **191**: 976, 993.

Frey, W., 1952. Der atmosphärische Vertikalstrom. *Arch. Kreislaufforsch*, **18**: 129–132.

Maw, M. G., 1961. Suppression of oviposition rate of *Scambus biolianae* (Htg) (Hymenoptera: Ichneumonidae) in fluctuating electric fields. *Canad. J. Entom.*, **93**: 602–604.

Schua, L. F., 1954. Wirken luftelektrische Felder auf Lebenwesen? *Umschau Wiss. Tech.*, **54**: 468–469.

Webb, H. M., F. A. Brown, Jr. and W. J. Brett, 1959. Effects of imposed electrostatic field on rate of locomotion in *Ilyanassa*. *Biol. Bull.*, **117**: 430.

Webb, H. M., F. A. Brown, Jr. and T. E. Schroeder, 1961. Organismic responses to differences in weak horizontal electrostatic fields. *Biol. Bull.*, **121**: 413.

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